

**BASE STATION IDENTIFICATION IN ORTHONGONAL FREQUENCY
DIVISION MULTIPLEXING BASED SPREAD SPECTRUM MULTIPLE
ACCESS SYSTEMS**

5 **Related Application**

Sub A
~~United States Patent application Serial No. (R. Laroia-J. Li-S. V. Uppala Case 16-9-4) was filed concurrently herewith.~~

Technical Field

10 This invention relates to wireless communications systems and, more particularly, to orthogonal frequency division multiplexing (OFDM) based spread spectrum multiple access (SSMA) systems.

Background of the invention

15 It is important that wireless communications systems be such as to maximize the number of users that can be adequately served and to maximize data transmission rates, if data services are provided. Wireless communications systems are typically shared media systems, i.e., there is a fixed available bandwidth that is shared by all users of the wireless system. Such wireless communications systems are often implemented as so-called "cellular" communications systems, in which the territory being covered is divided into separate cells, and each cell is served by a base station.

20 In such systems, it is important that mobile user units are rapidly able to identify and synchronize to the downlink of a base station transmitting the strongest signal. Prior arrangements have transmitted training symbols periodically for mobile user units to detect and synchronize to the associated base station downlink. In such arrangements, there is a large probability that delays occur in identifying the base station transmitting 25 the strongest signal because the training symbols are typically transmitted at the beginning of a frame. It is also likely that the training symbols transmitted from different base stations would interfere with each other. Indeed, it is known that once the training symbols interfere with each other they will continue to interfere. Thus, if the training symbols are corrupted, then the data is also corrupted, thereby causing loss in efficiency.

Summary of the Invention

Problems and/or limitations related to prior mobile user units that have attempted to identify a base station having the strongest downlink signal are addressed by utilizing a pilot tone hopping sequence being transmitted by a base station. Specifically, base 5 station identification is realized by determining the slope of the strongest received pilot signal, i.e., the received pilot signal having the maximum energy.

In an embodiment of the invention, the pilot tone hopping sequence is based on a Latin Squares sequence. With a Latin Squares based pilot tone hopping sequence, all a mobile user unit needs is to locate the frequency of the pilot tones at one time because the 10 pilot tone locations at subsequent times can be determined from the unique slope of the Latin Squares pilot tone hopping sequence. The slope and initial frequency shift of the pilot tone hopping sequence with the strongest received power is determined by employing a unique maximum energy detector. This unique slope of the pilot tone hopping sequence is then advantageously employed to identify the base station having the 15 strongest downlink signal.

In one embodiment, the slope and initial frequency shift of the pilot signal having the strongest received power is determined by finding the slope and initial frequency shift of a predicted set of pilot tone locations having the maximum received energy.

In another embodiment, the frequency offset of the pilot signal with the strongest, 20 i.e., maximum, received power is estimated at each of times "t". These frequency offsets are employed in accordance with a prescribed relationship to determine the unknown slope and the initial frequency shift of the pilot signal.

A technical advantage to using the pilot tone hopping sequence to identify the base station having the strongest downlink signal is that the inherent latency resulting 25 from using a sequence of training symbols is not present.

Brief Description of the Drawing

FIG. 1 illustrates a frequency domain representation in which a prescribed plurality of tones is generated in a prescribed bandwidth;

FIG. 2 illustrates a time domain representation of a tone f_i ;

30 FIG. 3 is a graphical representation of a time-frequency grid including a pilot tone hopping sequence;

FIG. 4 is a graphical representation of a Latin Squares hopping sequence;

FIG. 5 shows, in simplified block form, an OFDM-SSMA cellular system with Latin Squares pilots;

FIG. 6 shows, in simplified block diagram form, details of a mobile user unit in
5 which an embodiment of the invention may advantageously be employed;

FIG. 7 shows, in simplified block diagram for, details of an embodiment of a maximum energy detector that may be employed in the mobile user unit of FIG. 6;

FIG. 8 shows, in simplified block diagram form, details of another embodiment of a maximum energy detector that may be employed in the mobile user unit of FIG. 6; and

10 FIG. 9 is a flow chart illustrating steps in a process that may be employed in the slope-shift solver of FIG. 8.

Detailed Description

FIG. 1 illustrates a frequency domain representation in which a prescribed plurality of tones is generated in a prescribed bandwidth. In this example, bandwidth W is employed to generate a total of N tones, i.e., $i=1, \dots, N$. The tones are spaced at $\Delta f = 1/T_s$ apart, where T_s is the duration of an OFDM symbol. Note that the tones employed in this embodiment of the invention are generated differently than those generated for a narrow band system. Specifically, in a narrow band system the energy from each tone is strictly confined to a narrow bandwidth centered around the tone frequency, whereas in an Orthogonal Frequency Division Multiplexing (OFDM) system that is a wide band system the energy at a particular tone is allowed to leak into the entire bandwidth W , but it is so arranged that the tones do not interfere with one another.

FIG. 2 illustrates a time domain representation of tone f_i within symbol interval T_s . Again, note that within each symbol interval T_s , data may be transmitted on each of the tones substantially simultaneously.

FIG. 3 is a graphical representation of an example OFDM channel from a base station to a number of mobile user units, i.e., receivers. The OFDM channel is represented as a time-frequency grid, i.e., plane. Each column of the grid represents the time interval for one OFDM symbol interval, and each OFDM symbol is comprised of a 30 number of tones. In this example, there are $N=5$ tones in each symbol interval. The

tones are numbered along the frequency axis and the symbol intervals, i.e., periods, are numbered along the time axis. If the spacing between tones in FIG. 3 is Δf , then:

- 5 tone 0 corresponds to f ;
- tone 1 corresponds to $f + \Delta f$;
- tone 2 corresponds to $f + 2\Delta f$;
- tone 3 corresponds to $f + 3\Delta f$;
- tone 4 corresponds to $f + 4\Delta f$.

Similarly, if the duration of a symbol interval is T_s then:

- time 0 corresponds to t_0 ;
- 10 time 1 corresponds to $t_0 + T_s$;
- time 2 corresponds to $t_0 + 2T_s$;
- time 3 corresponds to $t_0 + 3T_s$;
- time 4 corresponds to $t_0 + 4T_s$;
- time 5 corresponds to $t_0 + 5T_s$;
- 15 time 6 corresponds to $t_0 + 6T_s$.

In general, a pilot signal includes known waveforms that are transmitted from a base station so that mobile user units, i.e., receivers, can identify the base station and estimate various channel parameters. In an Orthogonal Frequency Division Multiplexing based Spread Spectrum Multiple Access (OFDM-SSMA) system, in accordance with an aspect of the invention, the pilot signal is comprised of known symbols transmitted on prescribed tones during prescribed symbol intervals. In a given symbol interval, the tones used for the pilot signal are called the “pilot tones”, and the assignment of pilot tones as a function of time is called the “pilot hopping sequence”. Again, it is noted that the inherent delays resulting when using the training sequence of symbols is not experienced when using the pilot tone hopping sequence to identify the base station having the strongest downlink signal.

Since the OFDM-SSMA physical layer is based on the pilot signals, symbols on the pilot tones are transmitted at higher power than symbols on non-pilot tones. Pilot tones are also boosted in power so that they may be received throughout the cell.

Therefore, for the purpose of identification, pilot signals can be distinguished by the fact that the energy received on the pilot tones is higher than the energy on the non-pilot tones.

In FIG. 3, an example set of pilot tones is indicated by the hatched squares in the time-frequency grid. In this example, the base station transmits one pilot tone in each OFDM symbol interval. During symbol interval (0), tone (1) is used as a pilot tone; symbol interval (1), tone (4) is used as a pilot tone; symbol interval (2), tone (0) is used as a pilot tone; symbol interval (3), tone (2) is used as a pilot tone; symbol interval (4), tone (4) is used as a pilot tone; symbol interval (5), tone (1) is used as a pilot tone; etc...

FIG. 4 shows an example of a Latin Squares pilot hopping sequence. The pilot signal corresponding to a Latin Squares pilot hopping sequence will be called a “Latin Squares pilot signal”, or simply “Latin Squares pilot”. In a Latin Squares pilot hopping sequence, the number of tones, N , is a prime number, and the pilot signals are transmitted on a fixed number, N_p , of the N tones in each OFDM symbol interval. The tone number of the j -th pilot tone in the t -th symbol interval is given by,

$$\sigma_s(j,t) = st + n_j \pmod{N}, \quad j = 1, \dots, N_p, \quad (1)$$

where s and n_j are integers. A Latin Squares pilot signal of the form of Equation (1) can be viewed as a set of N_p parallel, cyclically rotating lines in a prescribed time-frequency grid, i.e., plane. The parameter, s , is the *slope* of the lines and the parameters, n_j , are the *frequency offsets*. In the example Latin Squares pilot hopping in FIG. 4, $N = 11$, $N_p = 2$, $n_1 = 1$, $n_2 = 5$ and $s=2$.

The frequency offsets and slope are design parameters of the Latin Squares pilot signal. For the purpose of channel estimation, the frequency offsets and slope should be selected so that the pilot tones are close to uniformly distributed in the time-frequency plane. A uniform distribution minimizes the worst-case interpolation error in the channel estimation. Specific values for the frequency offsets and slopes can be tested by numerical simulation with a specific channel estimator and channel conditions.

FIG. 5 depicts an OFDM-SSMA cellular system using Latin Squares pilots. The figure shows two base stations 501 and 502 in the cellular system, denoted BS1 and BS2, respectively. Each base station 501, 502 in the cellular system transmits a Latin Squares

pilot. A mobile user unit 503, denoted MS, receives pilots signals and other transmissions from one or more base stations in the cellular system. The Latin Squares pilots transmitted by all the base stations 501, 502 use the same total number of tones, N , number of pilot tones per OFDM symbol, N_p , and the frequency offsets, n_j . However,

5 the slope, s , of each pilot signal is locally unique in the sense that no two neighboring base stations use the same slope. Each slope, s , is taken from some set $S \subset \{0, 1, \dots, N-1\}$. The use of locally unique slopes minimizes collisions between pilot signals from neighboring base stations. In addition, the slope provides a unique identifier for each base station. In FIG. 6, the slope of the pilot signal from BS1 (501) is denoted

10 s_1 , and the slope of the pilot signal from BS2 (502) is denoted s_2 .

The base station identification problem is for the mobile user unit 503 to estimate the slope, $s \in S$, of the strongest received pilot signal. To perform this identification, the mobile user unit 503 can be pre-programmed with the common pilot signal parameters, N , N_p and n_j , as well as the set of possible slopes, S .

15 In general, base station identification is conducted prior to downlink and carrier synchronization. Consequently, a mobile user unit 503 may receive the pilot signals with unknown frequency and timing errors, and mobile user units must be able to perform base station identification in the presence of these errors. Also, after identifying the pilot hopping sequence of the strongest base station, the mobile user unit must synchronize its

20 timing and carrier so that the location of subsequent pilot tones can be determined.

To define this synchronization problem more precisely, let Δt denote the timing error between a base station and mobile user unit in number of OFDM symbol intervals, and Δn denote the frequency error in number of tones. For the time being, it is assumed that Δt and Δn are both integer errors. Fractional errors will be considered later. Under

25 integer time and frequency errors, Δt and Δn , if a base station transmits a pilot sequence given by Equation (1), the j -th pilot tone in the t -th symbol interval of the mobile will appear on tone number,

$$\sigma_s(j, t + \Delta t) + \Delta n = b(t) + n_j, \quad (2)$$

where,

30 $b(t) = s(t + \Delta t) + \Delta n,$ (3)

and where $b(t)$ is the pilot frequency shift at time t . Equation (2) shows that if the frequency shift $b(t)$ is known, the locations of the pilot tones at t are known. Also, if the frequency shift is determined at any one time, say $b(0)$, the frequency shift at other times can be determined from $b(t) = b(0)+st$. Therefore, for synchronization, it suffices to 5 estimate the frequency shift at any one time. The value $b(0)$ will be called the initial frequency shift.

The fact that synchronization requires only the estimation of the initial frequency shift is a particular and useful feature of the Latin Square pilot hopping sequences. In general, synchronization involves estimation of time and frequency errors, and therefore 10 demands a two parameter search. Synchronization for the Latin Squares sequences considered here, however, only requires the estimation of one parameter.

In summary, in an OFDM-SSMA cellular system, each base station transmits a Latin Squares pilot signal with a locally unique slope. A mobile user unit performs base station identification by estimating the slope of the strongest received pilot signal. In 15 addition, the mobile user unit can synchronize to the pilot signal by estimating its initial frequency shift.

FIG. 6 shows, in simplified block diagram form, the details of a mobile user unit 600 containing the proposed maximum energy detector for base station identification. An incoming signal is supplied via an antenna 601 to a down conversion unit 602. The 20 incoming signal includes pilot signals from one or more base stations. Down conversion unit 602 yields the baseband signal $r(t)$ from the signal received by the mobile user unit 600. The received signal $r(t)$ is supplied to fast Fourier transform (FFT) unit 603 that during each OFDM symbol interval performs an FFT on it to yield $Y(t,n)$. In this example, $Y(t,n)$ denotes the complex value received on the n -th tone in the t -th symbol 25 interval and is supplied to maximum energy detector 604 and to receiver 605. Maximum energy detector 604 uses FFT data $Y(t,n)$ from N_{sy} consecutive OFDM symbols to estimate the slope and initial frequency shift of the pilot signal with the maximum received strength. As indicated above, the FFT symbols to be used for the base station identification are denoted $Y(t,n)$, $t = 0, \dots, N_{sy} - 1$ and $n = 0, \dots, N-1$, and the estimates of the 30 slope and initial frequency shift of the strongest received pilot signal are denoted \hat{s} and

\hat{b}_0 , respectively. The pilot slope \hat{s} and initial frequency shift \hat{b}_0 estimates are supplied to a receiver 605 and employed to synchronize receiver 605 to the incoming carrier and to locate subsequent symbols in the pilot signal.

FIG. 7 shows, in simplified block diagram form details of an embodiment of a maximum energy detector 604 that may be employed in the mobile user unit 600 of FIG. 6. It has been seen that for the Latin Squares pilot tones, each candidate slope, s , and initial frequency shift, $b_0 = b(0)$, corresponds to a set of predicted pilot tone locations, (t, n) , with

$$n = st + b_0 + n_j, \quad j = 1, \dots, N_p, \quad t = 0, \dots, N_{sy} - 1. \quad (4)$$

Symbols on these pilot tones should be received with greater power than the symbols on the non-pilot tones. That is, the energy, $|Y(t, n)|^2$, should on average be highest on the pilot tones of the pilot signal with the strongest received signal strength. Therefore, a natural way to estimate the slope and frequency shift of the strongest pilot signal is to find the slope and frequency shift for which there is a maximum received energy on the predicted set of pilot tone locations of Equation (4). The input to the maximum energy detector 604 of FIG. 6 is the FFT data, $Y(t, n)$, $t = 0, \dots, N_{sy} - 1$ and $n = 0, \dots, N - 1$. The slope-shift accumulator 701, accumulates the energy along each possible slope, s , and initial frequency shift, b_0 . The accumulated energy is given by the signal:

$$J_0(s, b_0) = \sum_{t=0}^{N_{sy}-1} |Y(t, st + b_0 \pmod{N})|^2. \quad (5)$$

20

Then, frequency shift accumulator 702 accumulates the energy along the pilot frequency shifts, namely:

$$J(s, b_0) = \sum_{j=1}^{N_p} J_0(s, b_0 + n_j). \quad (6)$$

Maximum detector 703 estimates the slope and frequency shift of the maximum energy pilot signal as the slope and frequency shifts corresponding to the maximum accumulated pilot energy, that is:

$$\hat{s}, \hat{b}_0 = \arg \max_{s, b_0} J(s, b_0), \quad (7)$$

where the maximum is taken over $s \in S$ and $b_0 = 0, \dots, N - 1$.

Unfortunately, in certain applications, the above computations of Equations (5), (6) and (7) may be difficult to perform in a reasonable amount of time with the processing power available at the mobile user unit 600. To see this, note that to compute $J_0(s, b_0)$ in Equation (5) at a single point (s, b_0) requires N_{sy} additions. Therefore, to compute $J_0(s, b_0)$ at all (s, b_0) requires $NN_{sl}N_{sy}$ additions, where N_{sl} is the number of slopes in the slope set S . Similarly, computing $J(s, b_0)$ in Equation (6) requires $NN_{sl}N_p$ additions. Therefore, the complete energy detector would require $O(NN_{sl}(N_p + N_{sy}))$ basic operations to perform. Therefore, for typical values such as $N=400$, $N_{sl}=200$, $N_p=10$ and $N_{sy}=20$, the full energy detector would require 2.4 million operations. This computation may be difficult for the mobile user unit 600 to perform in a suitable amount of time.

FIG. 8 shows, in simplified block diagram form details of another embodiment of a maximum energy detector that may be employed in the mobile user unit of FIG. 6. Symbolwise shift detector 801 estimates, at each time t , the frequency shift of the pilot signal with strongest received strength. Specifically, the block computes:

$$[E(t), n(t)] = \max_n \sum_{j=1}^{N_p} |Y(t, n + n_j \pmod{N})|^2 , \quad (8)$$

where $E(t)$ is the maximum energy value and $n(t)$ is the argument of the maximum. To understand the purpose of the computation in Equation (8), suppose that the tones of the strongest energy pilot signal appear at the locations, (t, n) , given in Equation (4). Since the received energy $|Y(t, n)|^2$, will usually be maximum at these pilot tone locations, the maximization in Equation (9) will typically result in:

$$n(t) = st + b_0 \pmod{N}, \quad (9)$$

and $E(t)$ will typically be the pilot signal energy at the time t . The value $n(t)$ in Equation (9) is precisely the frequency shift estimate of the pilot signal at time t . Note that $n(t)$ is sometimes referred to as the symbolwise frequency shift estimate.

Slope-shift solver 802 uses the relation in Equation (9) and the frequency offset estimates, $n(t)$, to determine the unknown slope, s , and initial frequency shift, b_0 . Since,

the pilot signals are only on average higher in power than the non-pilot tones, the relation of Equation (9) may not hold at all time points t . Therefore, the slope-shift solver 802 must be robust against some of the data points $n(t)$ not satisfying Equation (9). For robustness, the value $E(t)$ can be used as measure of the reliability of the data $n(t)$.

5 Larger values of $E(t)$ imply a larger amount of energy captured at the frequency shift estimate, $n(t)$, and such values of $n(t)$ can therefore be considered more reliable.

One possible way of implementing a robust slope-shift solver 802 is referred to as the *difference method*. This method uses the fact that if $n(t)$ and $n(t-1)$ both satisfy Equation (10), then $n(t)-n(t-1)=s$. Therefore, the slope, s , can be estimated by:

$$10 \quad \hat{s} = \arg \max_{s \in S} \sum_{t=1}^{N_{sy}-1} E(t) \mathbf{1}_{\{n(t)-n(t-1)=s\}} \quad (10)$$

where $\mathbf{1}$ is the indicator function. The estimator as defined by Equation (10) finds the slope, s , on which the total received pilot energy, $E(t)$, at the points, t , satisfying $n(t)-n(t-1)=s$ is maximized. After estimating the slope, the initial frequency shift can be estimated by:

$$15 \quad \hat{b}_0 = \arg \max_{b_0=0, \dots, N-1} \sum_{t=0}^{N_{sy}-1} E(t) \mathbf{1}_{\{n(t)=st+b_0\}}. \quad (11)$$

The difference method is the process given by Equations (10) and (11).

A second possible method for the slope-shift solver 802 is referred to as the *iterative test method*. FIG. 9 is a flow chart illustrating the steps for the iterative test solver

- Step 901: Start process.
- 20 • Step 902: Initialize $T = \{0, \dots, N_{sy}-1\}$, and $E_{\max} = 0$.
- Step 903: Compute

$$\begin{aligned} t_0 &= \arg \max_{t \in T} E(t) \\ [E_0, s_0] &= \max_{s \in S} \sum_{t \in T} E(t) \mathbf{1}_{\{n(t)=n(t_0)+s(t-t_0)\}} \\ T_0 &= \{t \in T : n(t) = n(t_0) + s_0(t - t_0)\} \\ T &= T \setminus T_0 \end{aligned} \quad (12)$$

where E_0 is the value of the maximum, i.e., strongest value, and s_0 is the argument of the maximum.

- Step 904: If $E_0 > E_{\max}$, go to step 905.
- Step 905: Set

$$\begin{aligned} E_{\max} &= E_0, \\ \hat{s} &= s_0, \\ \hat{b}_0 &= n(t_0) - s_0 t_0. \end{aligned} \tag{13}$$

Then, go to step 906.

5 • Step 904: If not go to step 906.
 • Step 906: If T is non-empty return to step 903, otherwise END via step 907.

The values \hat{s} and \hat{b}_0 in Step 905 are the final estimates for the slope and initial frequency shift of the strongest pilot signal.

The logic in the iterative test method is as follows. The set T is a set of times and
 10 is initialized in Step 902 to all the N_{sy} time points. Step 903 then finds the time,
 $t_0 \in T$, and slope, $s_0 \in S$, such that the set of times t on the line $n(t) = n(t_0) + s_0(t - t_0)$,
 has the largest total pilot signal energy. The points on this line are then removed from T .
 In Step 904, if the total energy on the candidate line is larger than any previous candidate
 15 line, the slope and frequency shift estimates are updated to the slope and frequency shifts
 of the candidate line in step 905. Steps 903 through 906 are repeated until all points have
 been used in a candidate line.

Both the difference method and iterative test method demand significantly less
 computational resources than the full maximum energy detector. In both methods, the
 bulk of the computation is in the initial symbolwise shift detection in Equation (8). It can
 20 be verified that to conduct this maximization at all the N_{sy} time points
 $N_{sy}NN_p$ operations. Therefore, for the values $N=400$, $N_p=10$ and $N_{sy}=20$, the
 simplified maximum energy detector would require 80000 operations, which is
 considerably less than the 2.4 million needed by the full energy detector.

The above base station identification methods can be further simplified by first
 25 quantizing the FFT data $Y(t,n)$. For example, at each time t , we can compute a quantized
 value of $Y(t,n)$ given by:

$$Y_q(t,n) = \begin{cases} 1 & \text{if } |Y(t,n)|^2 > q\mu(t) \\ 0 & \text{else} \end{cases} \tag{15}$$

where $q > 1$ is an adjustable quantization threshold, and $\mu(t)$ is the mean received energy at time t :

$$\mu(t) = \frac{1}{N} \sum_{n=0}^{N-1} |Y(t, n)|^2. \quad (16)$$

The quantized value $Y_q(t, n)$ can then be used in place of $|Y(t, n)|^2$ in the above base station identification processes. If the parameter q is set sufficiently high, $Y_q(t, n)$ will be zero at most values of n , and therefore the computations such as Equation (8) will be simplified.

In the above discussion, it has been assumed that the time error between the base station and mobile is some integer number of OFDM symbol intervals, and the frequency error is some integer number of tones. However, in general both the time and frequency errors will have fractional components as well. Fractional errors result in the pilot tones being split between two time symbols and spread out in frequency. This splitting reduces the pilot power in the main time-frequency point, making the pilot more difficult to identify. Meanwhile, without proper downlink synchronization, data signals from the base station are not received orthogonally with the pilot signal, thus causing extra interference in addition to that generated by neighboring base-stations. Overall, fractional time and frequency errors can thereby significantly degrade the base station identification. In particular, the strongest energy detection process may not perform well.

To avoid this fractional problem, the above identification processes be run at several fractional offsets. Specifically, for a given received signal $r(t)$, the mobile user unit can slide the FFT window $N_{fr,t}$ times along the time axis, each time obtaining a different set of frequency sample vectors. The step size of sliding the FFT window should be $1/N_{fr,t}$ of the symbol interval. Similarly, the mobile user unit can slide the FFT window $N_{fr,f}$ times along the frequency axis with a spacing of $1/N_{fr,f}$ of a tone. The identification process can be run on the frequency samples obtained from each of the fractional time and frequency offsets. This process yields $N_{fr,t}N_{fr,f}$ candidate slope and frequency shifts.

To determine which of the $N_{fr,t}N_{fr,f}$ candidate slope and shifts to use, the mobile user can select the slope and shift corresponding to the strongest pilot energy. For a given candidate (s, b_0) the pilot energy is given by $J(s, b_0)$ in Equation (6). If the difference method is used, an approximation for the pilot energy is given by the value of the strongest attained in equation (11). The value E_{\max} may be employed in the iterative test method.

The above-described embodiments are, of course, merely illustrative of the principles of the invention. Indeed, numerous other methods or apparatus may be devised by those skilled in the art without departing from the spirit and scope of the invention.

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